Published online September 8, 2006

Selection for Drought Resistance in Dry Bean Landraces and Cultivars

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ABSTRACT

Drought is a worldwide constraint to dry bean (*Phaseolus vulgaris* L.) production. The objective of this research was to determine the response of three dry bean landraces and 13 cultivars evaluated under non-stressed (NS) and intermittent drought-stressed (DS) environments at Kimberly, Idaho in 2003 and 2004. The NS received seven irrigations in 2003 and five in 2004, and DS only four in 2003 and two in 2004. Most water use occurred within the top 0.5 m soil in both the NS and DS. Drought reduced biomass and seed yield, harvest index, and seed weight. Maturity was delayed in severe drought, but was similar or shortened by 1 to 6 d under moderate drought. Mean seed yield was reduced by 62% in 2003 and by 27% in 2004. Common Red Mexican and CO 46348 had high seed yield in both NS and DS environments, whereas 'Matterhorn' and 'Othello' yielded comparatively high under DS but moderately in NS environment. Drought resistance was inadvertently reduced from Common Red Mexican landrace to intermediate levels in 'NW-63' and 'UI 239' released in 1979 and 1993, respectively, and more recently released 'LeBaron' (1999) and 'UI 259' (1996) were susceptible. Conversely, drought resistance was increased in newer pinto (Othello 1986; CO 46348) and great northern (Matterhorn 1998) releases compared to the landraces and older cultivars tested for those market classes. Seed yield in NS and DS was positively correlated. Seed yield was also correlated with harvest index in DS and NS. All early maturing cultivars except Othello (e.g., UI 59, US 1140, Common Pinto, Topaz, UI 320, and LeBaron) were susceptible. Common Red Mexican did not have any reduction in seed weight due to drought stress. Drought resistant genotypes should be used for determining irrigation frequency, amount of water to be applied, and mechanisms of resistance and for identifying, mapping, and pyramiding favorable genes for dryland and irrigation-assisted sustainable production systems.

Intermittent or terminal drought affects >60% of dry bean production worldwide (White and Singh, 1991). For example, drought is endemic in >1.5 million ha of dry bean planted each in northeastern Brazil and the central and northern highlands of Mexico. The Western U.S. is characterized by arid and semiarid conditions with inadequate summer rainfall where the ratio of agricultural use over total use of water is the highest (>85%) in the country (Solley, 1997) and a moderate to severe drought affects >50% of the cropped land (Cook et al., 2004; Miller et al., 2002). Thus, in the western USA, dry bean cannot be grown without supplemental irrigation. With demographic expansion and climatic changes, problems of water shortage have been accentuated. Irrigation water supplies have been highly variable, and forecasts, under the shadow of global climate change, indicate even more variability and shortage in the future. Moreover, the fresh water resource is becoming increasingly stretched between irrigated agriculture, endangered species, water quality needs of municipalities, and recreation. Water is routinely transferred away from agriculture, so that irrigated agriculture must develop cultivars requiring lower inputs of water if a viable economic base is to be sustained. Reduced water, nutrient, and pesticide use efficiency, as well as increased production costs have become severe problems for dry bean producers in the Western U.S. The importance and urgency of developing high yielding drought resistant cultivars that use water efficiently, reduce dependence on irrigation water and associated production costs, increase and stabilize yield in drought-prone environments, and increase profit margins for producers can never be over emphasized. Identification and judicious use of drought resistant landraces and cultivars for immediate use is therefore pivotal for any strategies designed to conserve water and maximize its usage.

The effects of drought stress vary depending on the frequency, duration, and intensity of stress and growth stages affected. In dry bean, excessive abortion of flowers, young pods, and seeds occurs because of drought stress during pre-flowering (10 to 12 d before anthesis) and reproductive periods. Moderate to severe drought stress reduced biomass and seed yield (from 20 to 90%), harvest index, number of pods and seeds, seed weight, and days to maturity (Nielsen and Nelson, 1998; Nuñez-Barrios et al., 2005; Ramírez-Vallejo and Kelly, 1998; Terán and Singh, 2002a). Drought stress reduced P uptake (Guida dos Santos et al., 2004) and N concentration, partitioning, and fixation in dry bean (Ramos et al., 1999; Serraj and Sinclair, 1998). Drought stress increases root shrinkage that consequently affects nutrient transport to the root surface due to reduced contact between root and soil (North and Nobel, 1997). Dry soil particles hold water and nutrient more strongly on the surface, and dry soil is more compact for root penetration (Passioura, 2002). Root rots caused by *Macrophomina phaseolina* (Tassi) Goid., *Fusarium solani* f. sp. *phaseoli* (Burk.) Snyder & Hansen, and other fungi may aggravate drought stress. Similarly, drought-stressed cultivars are prone to damage by leafhoppers (*Empoasca kraemeri* Ross and Moore) in the tropics and subtropics.

Among *Phaseolus* species the tepary bean, *P. acutifolius* A. Gray, has the highest level of drought resistance (Lazcano-Ferrat and Lovatt, 1999). However, the

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Published in Crop Sci. 46:2111–2120 (2006).
Crop Breeding & Genetics
doi:10.2135/cropsci2006.01.0029

Abbreviations: NS, non-stressed; DS, drought-stressed; DII, Drought intensity index; DSI, drought susceptibility index; PR, percent reduction; WUE, water use efficiency.

drought resistance genes from tepary bean have not yet been introgressed into dry bean. In dry bean, drought resistance was reported in the races Durango, Mesoamerica, and Jalisco (Terán and Singh, 2002a). The highest level of drought resistance among these races occurs in the race Durango, which originated in the semiarid central and northern highlands of Mexico (Singh et al., 1991). Race Durango cultivars also predominate in the U.S. and North America. These cultivars mostly possess indeterminate, prostrate growth habit Type III (Singh, 1982). The objectives of this study were to: (i) characterize three race Durango dry bean landraces and 13 cultivars developed between 1932 and 1998 for biomass and seed yield, harvest index, seed weight, and number of days to maturity under drought-stressed (DS) and non-stressed (NS) environments, and (ii) identify those with high levels of drought resistance.

MATERIALS AND METHODS

Three dry bean landraces, or selections thereof, and 13 cultivars released between 1932 and 1998, belonging to race Durango, and representing great northern, pinto, and red market classes were evaluated in DS and NS environments, using furrow irrigation, at University of Idaho-Kimberly Research and Extension Center, Idaho in 2003 and 2004. Kimberly has a mean elevation of 1195 m and is located at 42° 30′ N; 114° 8′ W. Kimberly has 47 mm average precipitation and an average temperature of 27°C during the growing season (June to September). The soil is a Portneuf, coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids, pH 7.6, with moderate permeability in the A-horizon and slow in the B-horizon (University of Idaho and USDA, 1986).

Dry bean in each market class had a representative landrace or selection thereof. For example, UI 59 was selected for *Bean common mosaic virus* (BCMV, a potyvirus) resistance from a Great Northern landrace grown by Mandan tribes of North Dakota (Dean, 2000). Common Pinto and Common Red Mexican are landraces that were cultivated by Native Americans in the western USA. Most of the 13 cultivars were selected based on their seed yield in trials performed between 1999 and 2001 in Southern Idaho (Singh et al., 2001).

The landraces and cultivars were arranged in a randomized complete block design with four replications each in NS and DS environments. Each plot consisted of eight rows of 7.62 m length and 0.56 m between rows. An average of 23 seeds per linear meter of row length was planted. The NS and DS trials were planted adjacent to each other in the same field separated by a band of eight rows of dry bean in DS to reduce lateral infiltration of water from NS to DS plots. The NS trial received seven irrigations (661 mm) in 2003 and five irrigations (571 mm) in 2004. The DS trial received four irrigations (378 mm) in 2003 and two irrigations (201 mm) in 2004. The amount of irrigation water was monitored using three pairs of small trapezoidal flumes. Each pair of flumes was located in the same furrow, one at the top and the other at the bottom of the furrow to measure water flow rate passing through furrows and water applied according to the procedures described in the Water Resources Research Laboratory Manual (2001). Mean daily precipitation; minimum, maximum, and mean temperature; solar radiation; evapotranspiration Kimberly-Penmann; mean humidity; and average wind speed were recorded from the Twin Falls Agrimet Station (<1000 m away from the plots) located at 42° 32′ 46″ N; and 114° 20′ 43″ W at the USDA-ARS Northwest Irrigation and Soils Research Laboratory at Kimberly, Idaho (www.usbr.gov/gp/agrimet/index.cfm, verified 12 June 2006).

Growth habit was recorded during flowering and verified at maturity. Days to maturity was recorded when 90% of the pods changed color from green to yellow. Biomass yield (kg ha^{-1}) was determined for each genotype by cutting 10 plants at ground level at maturity and drying at 60°C for three d. The six central rows (25.60 m^2) were cut at 108 d after planting in 2003 and 100 d in 2004, threshed eight d later, cleaned, dried, and seed yield recorded (kg ha^{-1}) at 12% moisture by weight. Harvest index was determined as the ratio between seed and biomass yield. Weight (g) of 100 seeds taken randomly was recorded. Drought intensity index (DII) for each year and drought susceptibility index (DSI) and percent reduction (PR) due to drought stress were calculated for each genotype according to Fischer and Maurer (1978).

Two dry bean landraces (Common Pinto and Common Red Mexican) and four of 13 cultivars (Othello, UI 320, NW 63, and UI 259) were chosen to estimate soil water content and water use in two of four replications in NS and DS environments. Soil samples were taken after planting, one d before and two d after each irrigation, and one d before harvest. In 2003, water content was estimated taking soil samples with an auger every 0.2 m until reaching 2 m depth with exception of the first 0.2 m where two samples were taken, 0 to 0.1 and 0.1 to 0.2 m. The 11 samples at each site were collected in metal cans and weighed before and after oven drying at 105°C for 24 h. In 2004, water content was estimated similarly as described above, but only the first and last samplings were conducted to depth of 2 m. All other samplings were conducted to a 1.2 m depth because in 2003 changes in water content beneath 1.2 m were small. The water content on mass and volumetric bases was calculated according to Cuenca (1989).

To measure water potential in centibars at 0.23, 0.46, and 0.92 m depth, soil moisture sensors or watermarks (Irrometer Company, Inc, Riverside, California) connected to AM400 dataloggers (Hansen Company, East Wenatchee, Washington) were used. The sensors were attached to 1/2 inch PVC tubes to facilitate their installation and recovery. The AM400 datalogger recorded water potential every 8 h. Six AM400 dataloggers and 36 soil moisture sensors were used in NS and DS environments. Every datalogger recorded data at three depths for two genotypes. In addition, each datalogger recorded soil temperature at 0.31 m depth.

A mixed model (McIntosh, 1983) was used for data analysis whereby years and replications were considered random and water stress treatments and genotypes were fixed effects. Data for each year were analyzed separately and the homogeneity of error variances was tested according to Bartlett (1947) before performing combined analyses. Simple correlation coefficients among traits were determined using the mean values for each year. All data were analyzed using the SAS (v 9.1.3) GLM procedure (SAS Institute, 2004).

RESULTS

The drought impact was twice as severe in 2003 (DII = 0.62) than in 2004 (DII = 0.27) even though two additional irrigations were applied in both NS and DS plots and the precipitation was higher in 2003 than in 2004 (Table 1). This was probably due to a delayed first post-emergence irrigation, unexpected soil compaction and crusting, other management practices, and large differences in the climatic parameters between the 2 yr. For example, maximum temperature above 35°C occurred at higher frequency in 2003 (18 d) than in 2004

Table 1. Number of irrigation events and amount of water applied to three dry bean landraces and 13 cultivars in non-stressed and intermittent drought-stressed environments. Rainfall, humidity, temperature, and solar radiation occurring between May 28 and September 13 at Kimberly, Idaho in 2003 and 2004.

	2003		2004	
Input or climatic variable	NS†	DS	NS	DS
Number of irrigations	7	4	5	2
Water applied (mm)	661	378	571	201
Rainfall (mm)		63		36
No. of days humidity < 45%		52		33
No. of days evapotranspiration > 8 mm d^{-1}		62		47
No. of days maximum temperature > 35°C		18		2
No. of days solar radiation > 700 calories cm^{-2}		44		23

† NS = non-stressed and DS = intermittent drought-stressed in vegetative and reproductive growth stages.

(2 d). Similarly, solar radiation above 700 calories/cm^2 was more frequent in 2003 (44 d) than in 2004 (23 d). Consequently, evapotranspiration values above 8 mm d^{-1} occurred at a higher frequency in 2003 (62 d) than in 2004 (47 d). Nonetheless, most water removal in both NS and DS environments occurred within the top 50 cm soil even under the severe drought stress in 2003 (Fig. 1).

Biomass Yield

Mean squares for the year, test-environment, replication, genotype, and interaction between year and genotype were highly significant ($P < 0.01$) for biomass yield (Table 2). No significant ($P > 0.05$) interaction occurred between year and test-environment (DS vs. NS), and between test-environment and genotype. Large differences between NS and DS occurred in overall mean biomass yield, among market classes, and genotypes in 2003 and 2004 (Table 3). Red-seeded genotypes had the highest biomass yield in NS in 2003, and great northern had the highest biomass yield in NS in 2004. However, differences between market classes were not significant under DS in 2003 and 2004. Except, great northern had slightly higher mean biomass yield than other market classes for the 2 yr in DS. Matterhorn, CO 46348, and Common Red Mexican had high biomass yield in DS in 2003, and 'Buster' and UI 239 in 2004 (Table 3). When averaged over 2 yr Matterhorn, 'UI 465' (Myers et al., 2001c), Buster, CO 46348, Common Red Mexican, and UI 239 had high biomass yield in NS and DS. Matterhorn, UI 465, and Othello had the lowest reduction in biomass yield due to drought stress. Othello had a similar biomass yield as Common Pinto, Topaz, and UI 320 (Myers et al., 2001a). However, Common Pinto and UI 320 along with UI 59 and UI 259 had the highest biomass reduction due to drought stress.

Seed Yield

Similar to biomass yield, mean squares for seed yield were highly significant for the year, test-environment, replication, genotype, and genotype × year interaction (Table 2). No significant interaction between the year and test-environment and genotype × test-environment was found. There were large differences for seed yield between 2003 and 2004 in NS and DS (Table 3). In general, seed yield for all genotypes in NS and DS was lower in 2003 compared with 2004.

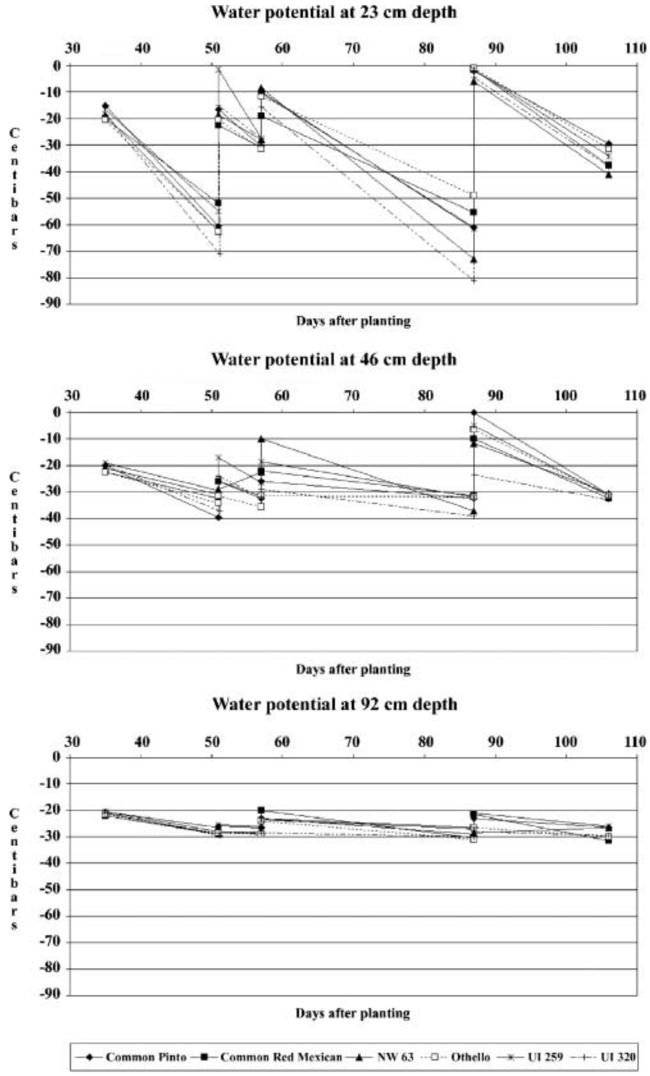

Fig. 1. A, B, and C, respectively, water potential at 23, 46, and 92 cm depths before and after each of four irrigations for two dry bean landraces and four cultivars evaluated under intermittent drought-stressed environment at Kimberly, Idaho in 2003. The second, fifth, and sixth irrigation were skipped. High peaks represent after and low peaks before irrigation.

In both years in NS and DS, mean seed yield of cultivars of red market class tended to be slightly higher than great northern and pinto market classes (Table 3). In great northern, mean seed yield of Matterhorn over the 2 yr was higher in NS and DS, whereas UI 59 and US 1140 had the lowest yield, but significant differences occurred only in the DS environment. Among pinto cultivars, Bill Z in NS and CO 46348 in DS had the highest yield averaged over the 2 yr. In contrast, Topaz and Common Pinto followed by UI 320 had the lowest yield in NS and DS. Although LeBaron had the lowest yield in red market class in both environments, differences in NS were not significant and Common Red Mexican followed by UI 239 had the highest yield in DS. Reduction in seed yield due to drought stress ranged from 34% for Othello to 90% for Topaz in 2003

Table 2. Mean squares for biomass and seed yield, harvest index, seed weight, and days to maturity for three dry bean landraces and 13 cultivars evaluated under non-stressed and intermittent drought-stressed environments at Kimberly, Idaho in 2003 and 2004.

Source	df	Biomass yield	Seed yield	Harvest index	Seed weight	Days to maturity
Year (Y)	1	961597787**	239430126**	1.1941**	903.53**	2075.94**
Test environment (E)	1	230573984**	71435076**	0.5378**	441.58**	295.41**
Y*E	1	6172265	198312	0.1595**	52.65	1246.97
Replication/Y*E	12	4928167**	288674**	0.0068	4.19**	16.59**
Genotype (G)	15	7331217**	1105752**	0.0225**	176.60**	265.50**
G*Y	15	4903800**	214500**	0.0065	15.94**	70.24**
G*E	15	1594230	125414	0.0067	7.38**	32.26**
G*Y*E	15	1322326	92786	0.0045	3.76	24.56**
Error	180	1721849	94345	0.0073	2.39	10.15

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.

(Table 3). A much smaller reduction occurred in 2004 due to a milder drought stress (Table 1). Matterhorn, Othello, and Common Red Mexican had DSI values less than 1.0 in both years. In contrast, US 1140, Common Pinto, Topaz, UI 320, and LeBaron, all relatively early maturing, tended to have DSI values higher or equal to 1.0.

Harvest Index

Mean squares for the year, test environment, genotype, and the interaction between year and test-environment were highly significant (Table 2). The lowest average harvest index was observed in DS in 2003 (Table 3). Othello, UI 239, CO 46348, and Common Red Mexican had the lowest reduction in harvest index due to severe drought stress in 2003. The largest harvest index reduction was observed in Topaz, Buster, Common Pinto, and UI 259 under DS environment in 2003.

Seed Weight

Mean squares for the year, test-environment, genotype, and interaction of genotype with year and test-environment were highly significant for seed weight (Table 2). Common Pinto and Common Red Mexican had the smallest and Buster, CO 46348, and UI 320 had the largest seed weight (Table 3). Reduction in seed weight due to drought stress ranged from 0 to 22% in 2003 and from −3 to 10% in 2004 (Table 3). However, in both years seed weight of Common Red Mexican was not affected by drought stress. Drought susceptible UI 59, Bill Z, Common Pinto, Topaz, and UI 259 had higher reduction in seed weight due to drought stress. In contrast, in addition to Common Red Mexican, other drought resistant cultivars namely, CO 46348, Matterhorn, and Othello had the lowest reduction in seed weight over the 2 yr.

Days to Maturity

Mean squares for the number of days to maturity were significant for the year, test-environment, and genotype (Table 2). Moreover, significant interactions occurred between year and genotype, and both interacted with the test-environment. In 2003, all genotypes except UI 259 took longer to mature in DS than in NS environment (Table 3). These differences among genotypes ranged from 1 d for CO 46348 and Common Red Mexican to 14 d for Bill Z, Common Pinto, and Topaz. In contrast to 2003, in 2004 all genotypes except UI 465 and Topaz either matured the same day under DS and NS or took 1 to 6 d longer in NS than in DS.

Correlation Coefficients

Biomass yield under NS was positively correlated to biomass yield under DS in both years (Table 4). Biomass yield under NS was positively correlated to seed yield under NS and DS in 2003, but not in 2004. Similarly, biomass yield under DS was positively correlated to seed yield under NS and DS, and to harvest index and seed weight under DS in 2003, but negatively correlated with harvest index under NS and DS in 2004. Seed yield in NS was positively correlated to seed yield under DS in both years. Furthermore, seed yield under NS and DS was positively correlated to harvest index under DS in both years. In addition, seed yield under DS was negatively correlated to days to maturity under DS in 2003 and positively correlated in 2004. Harvest index under NS was positively correlated to harvest index under DS in 2004. A positive association was found between seed weight under NS and DS in both years. Maturity under NS was positively associated to maturity under DS in 2004.

Classification of Landraces and Cultivars

As noted earlier, the DII was 0.62 in 2003 and 0.27 in 2004. Values for DII between 0.02 and 0.90 have been reported from other production regions (Frahm et al., 2004; Schneider et al., 1997; Terán and Singh, 2002a, 2002b). However, growing environments with DII values lower than 0.50, hence a milder drought stress, may identify different cultivars as drought resistant from those environments with higher DII values. In 2003, considering the DII, mean seed yield in NS and DS, PR, and DSI values, three dry bean landraces and 13 cultivars could be classified into three groups (Fig. 2). The first group was represented by Common Red Mexican and CO 46348 that yielded high in both DS and NS and had a below average reduction due to drought stress. While Othello and Matterhorn also possessed high and NW 63 and UI 239 moderate levels of drought resistance, they yielded moderately in NS environment. Buster and UI 259 yielded well in NS but they were susceptible to drought. Topaz, UI 59, Common Pinto, UI 320, U.S. 1140, and LeBaron were low yielding

Table 3. Year of release, growth habit, biomass and seed yield, harvest index, seed weight, and days to maturity of three dry bean landraces and 13 cultivars evaluated under non-stressed and intermittent drought-stressed environments at Kimberly, Idaho in 2003 and 2004.

			Biomass yield				Seed yield								Harvest index				Seed weight				Days to maturity			
			2003		2004		2003				2004				2003		2004		2003		2004		2003		2004	
Identification	Year of release	Growth habit†	NS‡	DS	NS	DS	NS	DS	PR	DSI	NS	DS	PR	DSI	NS	DS	NS	DS	NS	DS	NS	DS	NS	DS	NS	DS
Great northern			kg ha^{-1}				kg ha^{-1}		%		kg ha^{-1}		%		ratio		ratio		g				no. of d			
Matterhorn	1998	II	6092	5428	8352	8194	1905	979	49	0.8	3458	2699	22	0.8	0.32	0.18	0.42	0.37	33	31	33	32	90	98	92	91
UI 59	1932	III	5351	2679	10558	7334	1622	333	79	1.3	3253	2398	26	1.0	0.30	0.11	0.32	0.34	30	25	31	30	89	97	88	85
UI 465	1996	III	5770	4098	10435	9342	1797	687	62	1.0	3394	2982	12	0.5	0.31	0.18	0.33	0.33	32	29	35	32	94	100	88	90
US 1140	1960	III	4590	2766	9527	8294	1517	529	65	1.1	3463	2350	32	1.2	0.33	0.18	0.39	0.30	28	25	33	31	84	90	84	79
Mean			5451	3743	9718	8291	1710	632	64	1.0	3392	2607	23	0.9	0.32	0.16	0.36	0.33	31	28	33	31	89	96	88	86
Pinto																										
Bill Z	1987	III	5375	3197	9500	7294	1998	639	68	1.1	4224	2976	30	1.1	0.38	0.20	0.45	0.41	31	25	37	34	86	100	89	84
Buster	1999	II	6279	3200	10740	9843	1927	488	75	1.2	3874	2856	26	1.0	0.31	0.14	0.37	0.29	37	33	36	37	96	99	91	91
Common Pinto	–	II	4638	2201	8161	6328	1520	359	76	1.2	3312	1996	40	1.5	0.34	0.14	0.41	0.33	26	23	29	26	79	93	79	78
CO 46348	–	III	6300	4614	9711	6892	2039	1312	36	0.6	4143	3040	27	1.0	0.33	0.26	0.44	0.45	37	34	39	38	91	92	91	87
Othello	1986	II	5437	4103	7123	6412	1805	1199	34	0.5	3611	2762	24	0.9	0.34	0.28	0.52	0.44	32	31	36	34	83	89	77	77
Topaz	1986	III	4532	2604	7862	7065	1559	155	90	1.5	3187	2184	31	1.2	0.35	0.07	0.41	0.32	34	26	38	35	85	99	80	81
UI 320	1996	II	4473	2400	9709	7173	1407	502	64	1.0	3645	2415	34	1.2	0.32	0.19	0.40	0.36	35	32	41	38	89	99	81	81
Mean			5291	3189	8972	7287	1751	665	63	1.0	3714	2604	30	1.1	0.34	0.18	0.43	0.37	33	29	37	35	87	96	84	83
Red																										
Common Red Mexican	–	III	6668	4401	9078	7263	2162	1164	46	0.7	3671	2836	23	0.8	0.33	0.26	0.41	0.42	27	27	27	27	89	90	94	92
LeBaron	1998	II	5546	3248	8135	7091	1732	640	63	1.0	3552	2394	33	1.2	0.31	0.18	0.44	0.35	29	26	33	31	86	93	83	80
NW 63	1980	III	5737	3277	9389	7140	2008	824	59	1.0	3951	2943	26	0.9	0.35	0.25	0.43	0.42	29	27	33	31	87	93	91	85
UI 239	1993	III	7071	2837	9849	9438	1955	724	63	1.0	4084	3084	24	0.9	0.28	0.23	0.42	0.34	26	23	31	29	87	89	90	85
UI 259	1996	III	5697	3167	8479	6104	1850	471	75	1.2	4031	2928	27	1.0	0.33	0.13	0.49	0.48	32	25	35	32	98	97	93	91
Mean			6144	3386	8986	7407	1941	765	61	1.0	3858	2837	27	1.0	0.32	0.21	0.43	0.40	29	26	32	30	89	92	90	87
Overall mean			5597	3389	9163	7575	1800	688	63	1.0	3679	2678	27	1.0	0.33	0.19	0.41	0.37	31	28	34	32	88	95	87	85
LSD§ (0.05)			1084	1596	682	2325	204	630			422	385			0.07	0.15	0.11	0.13	2.0	4.0	1.7	1.3	3.0	8.0	2.7	1.8
LSD¶ (0.05)			480	707	302	1030	91	279			187	170			0.03	0.07	0.05	0.06	0.7	1.6	0.8	0.6	1.5	3.4	1.2	0.8

† Growth habit II = indeterminate upright, and III = indeterminate prostrate.
‡ NS = non-stressed, and DS = intermittent drought-stressed, PR = percent reduction in seed yield due to drought stress, and DSI = drought susceptibility index.
§ To compare means between genotypes.
¶ To compare means between market classes.

Table 4. Simple correlation coefficient between biomass and seed yield, harvest index, seed weight, and days to maturity for three dry bean landraces and 13 cultivars evaluated in non-stressed (NS) and intermittent drought-stressed (DS) environments at Kimberly Idaho in 2003 and 2004.

	B_{NS}†	B_{DS}	Y_{NS}	Y_{DS}	H_{NS}	H_{DS}	S_{NS}	S_{DS}	M_{NS}	M_{DS}
B_{NS}		0.57*	0.86**	0.59*	−0.43	0.48	−0.05	0.17	0.46	−0.28
B_{DS}	0.65**		0.65**	0.81**	0.00	0.51*	0.27	0.55*	0.32	−0.08
Y_{NS}	0.24	0.05		0.68**	0.08	0.58*	0.01	0.18	0.37	−0.20
Y_{DS}	0.36	0.33	0.78**		0.04	0.89**	0.07	0.49	0.05	−0.51*
H_{NS}	−0.73**	−0.58*	0.46	0.22		0.07	0.09	−0.05	−0.33	0.16
H_{DS}	−0.33	−0.62**	0.56*	0.51*	0.71**		−0.14	0.31	−0.13	−0.62*
S_{NS}	0.05	−0.06	0.23	0.12	0.19	0.11		0.83**	0.54*	0.56*
S_{DS}	0.16	0.08	0.28	0.21	0.12	0.09	0.95**		0.41	0.20
M_{NS}	0.50*	0.33	0.54*	0.71**	−0.14	0.31	−0.24	−0.08		0.46
M_{DS}	0.45	0.39	0.31	0.63**	−0.24	0.21	−0.14	0.03	0.90**	

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$. 2003 (above diagonal) and 2004 (below diagonal).
† B = biomass yield, Y = seed yield, H = harvest index, S = seed weight, and M = days to maturity. NS = non-stressed and DS = intermittent drought-stressed.

in both NS and DS in 2003 (Fig. 2) and 2004 (Fig. 3). In 2004, none of the genotypes fell in the top-left quadrant (Fig. 3). Instead, six genotypes, namely Bill Z, UI 259, Buster, CO 46348, NW 63, and UI 239 exhibited higher seed yield in both NS and DS. Common Red Mexican, Othello, Matterhorn, and UI 465 in the bottom-right quadrant expressing relatively high levels of drought resistance (i.e., lower PR and DSI values), had moderate yield in NS.

DISCUSSION

The absence of interaction between years and test-environments, and between test- environments, landraces and cultivars for biomass and seed yield suggests that the rank order of landraces and cultivars did not change significantly from one year to the other. Relative estimates of cultivar response to drought could be obtained in a single growing season in Southern Idaho, but the effect of drought may depend on the severity, frequency, and duration of stress, management practices, and environmental conditions.

Drought resistant (e.g., Common Red Mexican, NW 63, Othello) as well as susceptible (e.g., Common Pinto, UI 259, UI 320) landraces and cultivars mostly extracted water from the upper 45 to 50 cm soil profile and hence showed no significant differences in water potential at 46 and 92 cm soil depths, even under the most severe DS environment in 2003. Intermittent drought may have very likely hindered the maximum potential root growth of all genotypes irrespective of their levels of drought resistance. On the contrary, in NS environment, soil moisture often at field capacity would have masked genotypic differences in water potential at most soil depths.

By conducting replicated trials in NS and DS environments in 2003 and 2004 and using mean seed yield, DSI, and PR as selection criteria, and separating drought resistant from susceptible genotypes, it was possible to separate drought resistant genotypes into two groups. One group had relatively higher yield potential in NS environment, such as late maturing Common Red Mexican and CO 46348 and a second group showed moderate yield potential in NS environment, such as Matterhorn and Othello. If the trial had been conducted only in

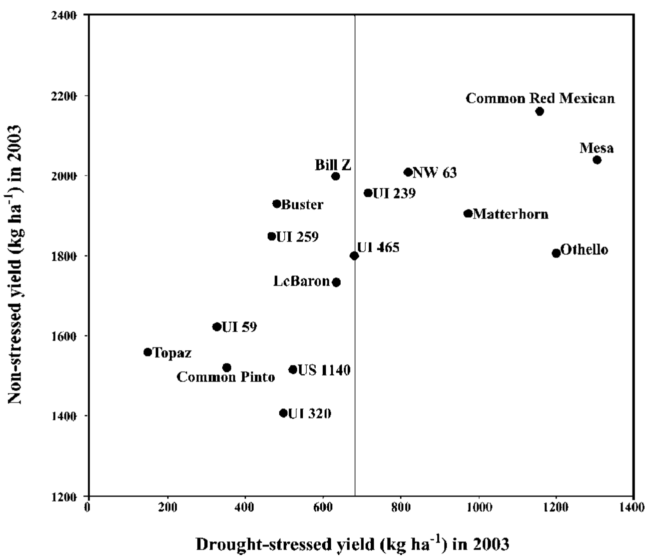

Fig. 2. Classification of three dry bean landraces and 13 cultivars according to mean seed yield evaluated in non-stressed and intermittent drought-stressed environments at Kimberly, Idaho in 2003.

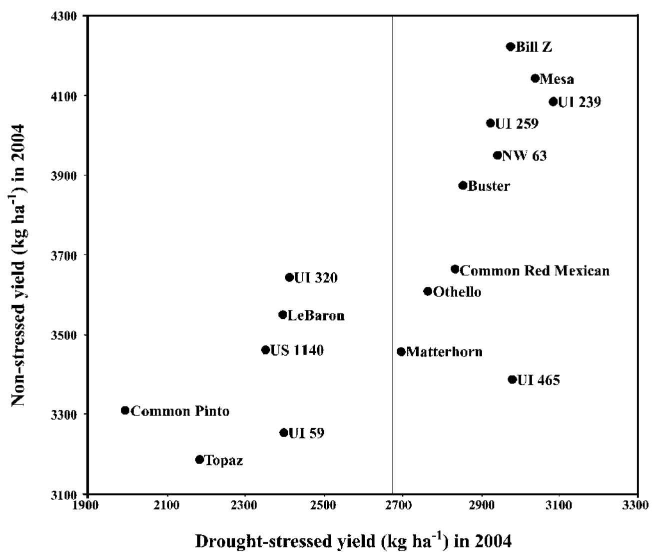

Fig. 3. Classification of three dry bean landraces and 13 cultivars according to mean seed yield evaluated in non-stressed and drought-stressed environments at Kimberly, Idaho in 2004.

2004, cultivars such as Bill Z, Buster, and UI 259 would have been classified as drought resistant. This discrepancy indicates that yield data from NS and DS environments across contrasting years (and locations) should be used for dry bean germplasm screening and other studies even in the absence of significant interactions among dry bean cultivars, test-environment, and year.

The summer rainfall in Southern Idaho (and other Western states) often provides < 20% of the required water for normal growth and reproduction of the dry bean crop in the region. Thus, by scheduling the irrigation timing, frequency, and amount of water applied, it should be possible to maximize the usage of water by growing drought resistant landraces and cultivars identified in this study, and to manipulate the severity of drought stress for further germplasm screening, breeding, genetics, and physiology studies. But, unexpected plot management problems and variation in solar radiation and temperature may confound selection for drought resistance and enhanced water-use efficiency. In this study, unexpected soil compaction and crusting, a delay in the first post-emergence irrigation, other management practices, lower humidity, and higher solar radiation and temperatures in 2003, when compared with 2004, accentuated the drought stress; such that the mean NS seed yield was 33% less than the DS yield in 2004 in spite of two additional irrigations, and 26.4 mm higher rainfall.

The optimum mean temperature for normal growth and reproduction of cultivars of race Durango (Singh et al., 1991), also referred as Gene Pool 5 (Singh, 1989), ranges between 18 and 25°C. Temperatures above 28°C cause excessive flower drop, pollen viability reduction, and abortion of fertilized ovules (Masaya and White, 1991). Plants in pre-flowering and flowering stages are extremely sensitive to drought and high temperatures. Reduced photosynthesis, excessive flower bud abscission (Rainey and Griffiths, 2005), and pollen sterility due to tapetal degeneration (Suzuki et al., 2001) followed by flower, ovule, and pod abscission (Ofir et al., 1993; Rainey and Griffiths, 2005) result in reduced pod and seed number, seed size, and yield due to high temperatures (Porch and Jahn, 2001; Prasad et al., 2002). Thus, mean temperatures above 25°C for 11 d and temperatures above 35°C for 18 d during flowering and seed-filling periods in 2003 may have accentuated drought stress. Furthermore, maximum photosynthesis occurs in dry bean when solar radiation is between 600 and 650 calories/cm^2 (White and Izquierdo, 1991). Consequently, a larger reduction in overall biomass and seed yield in both NS and DS environments due to drought stress, elicited by the above factors, occurred in 2003 compared with 2004. In future studies, it may be worthwhile to determine flower and pod drops, and pod and seed numbers in NS and DS and separate the effects of high temperature and solar radiation from management practices and drought stress.

Under terminal drought stress, number of days to maturity is often shortened (Terán and Singh, 2002a, 2002b). However, in this study, number of days to maturity was delayed in DS compared to NS in 2003. The discrepancy could be largely because, in contrast to a terminal drought, an intermittent drought stress was imposed in both vegetative and reproductive periods; thus, repeated disruption followed by recovery occurred in this study. Furthermore, all three landraces and 13 cultivars had indeterminate growth habits Type II or Type III. Thus, a severe intermittent drought during flowering and seed filling period resulted in a split-pod set in 2003 delaying overall maturity. Delayed maturity was observed when drought stress occurred in pre-flowering stage (Dubetz and Mahalle, 1969). Moreover, the number of days to maturity was not correlated with seed yield under DS. In a previous study, number of days to maturity was positively correlated with seed yield in NS and early maturity may have helped early maturing cultivars escape terminal drought (White and Singh, 1991). In this study, under intermittent drought stress, all early maturing landraces and cultivars (except Othello), that included US 1140, Common Pinto, Topaz, UI 320, and LeBaron, were susceptible to drought. Thus, genes and QTL for drought resistance seem to be different from those controlling maturity in dry bean. Furthermore, when screening germplasm for drought resistance and water use efficiency in the western USA, an intermittent drought throughout the growing season should be used to avoid escapes due to early maturity.

A positive association between biomass and seed yield in DS and NS, and biomass and seed yield and harvest index in DS in 2003, and generally a negative association between the biomass yield and harvest index in both the NS and DS in 2004 may suggest that overall growth of three dry bean landraces and 13 cultivars was limiting in 2003. The biomass yield in severe DS could therefore be a useful selection criterion for drought resistance, and dry bean producers may apply more frequent irrigation to reduce drought stress to maximize seed yield. On the contrary, the frequency of irrigation and amount of water applied should be reduced in more favorable growing conditions to reduce biomass yield and maximize harvest index in race Durango cultivars in the western USA.

Positive correlation coefficients between seed yield and harvest index in DS were larger and highly significant in both years than in NS. Drought susceptible genotypes, in general, had a relatively lower harvest index irrespective of their maturity. Thus, the ability of drought resistant landraces and cultivars for partitioning a relatively higher amount of photosynthate from vegetative organs to developing seed appeared to have played a crucial role in minimizing the adverse effects of drought stress.

Although all three landraces, or selections thereof, and the 13 cultivars belonged to race Durango and were relatively well adapted to Southern Idaho, large differences were found with regard to their response to severe drought stress in 2003. For example, of the three landraces, only Common Red Mexican was drought resistant. The most recently developed cultivars in the red market class, namely LeBaron (Hang et al., 2000) and UI 259 (Myers et al., 2001b), were highly susceptible to drought. As noted earlier, NW 63 (Burke, 1982) and UI

239 (Myers et al., 1997), also derived from Common Red Mexican and released several years earlier than LeBaron and UI 259, had an intermediate level of resistance to severe drought stress in 2003. Thus, drought resistant alleles and QTL seem to have been inadvertently lost in modern cultivars of the red Mexican market class. Dry bean cultivars developed by the USDA-ARS researchers at Prosser, Washington, in general, exhibit moderate to high levels of resistance to drought (Miller and Burke, 1983; Singh et al., 2001), low soil fertility (Westermann and Singh, 2000), and Fusarium root rot (Burke and Miller, 1983; P. Miklas, unpublished data). Superior performance of those cultivars could be largely because a "purgatory-plot" with general water, nutrient, and root rot stresses and alternate-year bean cropping at Roza, Washington has been used for germplasm screening and selection for decades. It is therefore expected that cultivars such as NW 63 and Othello (Burke et al., 1995) developed at Prosser, and their derivatives such as UI 239 that were developed at Kimberly, Idaho, but tested at Roza before their release, also exhibited moderate to high levels of drought resistance.

Common Red Mexican has the typical characteristics of race Durango (Singh et al., 1991). Its leaves are small, relatively dark, and it often does not produce any guides. Also, the lower internodes are shorter, providing good ground cover, thus minimizing evaporation and conserving moisture. Leaves stay green for a longer period, which may facilitate higher seed filling capacity compared to other cultivars. Whether these characteristics are linked with, or have pleiotropic effects of favorable genes and QTL determining drought resistance in Common Red Mexican is not known. Nonetheless, Common Red Mexican was used extensively as a source of adaptation to semiarid environments and resistance to *Beet curly top virus* (a leafhopper-vectored geminivirus) in dry bean breeding programs in the western USA. For example, cultivars Othello (Burke, 1982), Bill Z (Wood et al., 1989), UI 239 (Myers et al., 1997), UI 259 (Myers et al., 2001b), and NW 63 (Burke et al., 1995) have Common Red Mexican in their parentage (Miklas, 2000).

In contrast to the red Mexican market class, the landraces of pinto (Common Pinto) and great northern (UI 59, a selection from Common Great Northern landrace, see Dean, 2000) market classes used in this study were highly susceptible to drought. But some cultivars from these (in addition to Othello) market classes, namely great northern Matterhorn and pinto CO 46348, although not specifically bred for drought resistance, were drought resistant. Unlike Common Red Mexican why were Common Pinto and UI 59 not resistant to drought? One possible reason could be that they were selected in cooler environments in the absence of drought. For example, the great northern landrace from which UI 59 and other early University of Idaho cultivars were selected was obtained from the Mandan tribes of North Dakota (Dean, 2000), where it is much cooler and wetter than Southern Idaho. Thus, selection for drought resistance may have never been practiced in the great northern landrace. Also, great northern may have had its origin in the humid highlands of Middle America, and not in the semiarid Mexican highlands.

Native Americans and early settlers grew pinto 'San Juan' in the dryland farming systems in the San Juan Basin of Arizona, Colorado, New Mexico, and Utah (M. Brick, personal communication, 2005). San Juan and its derived cultivars Cahone (Wood et al., 1983) and Fisher (Fisher et al., 1995) are partially sensitive to summer months in Southern Idaho. Consequently, they take over 3 wk longer to flower and mature than Common Pinto. Photoperiod insensitive and early maturing, Common Pinto landrace is possibly a mutant of San Juan or similar landrace that lost its drought resistance; or, alternatively it is an independent introduction from the highlands of Mexico by Native Americans or early settlers that is adapted to the Pacific Northwest.

Matterhorn may in part combine drought resistance from the small-seeded tropical black bean used to introgress upright plant type and lodging resistance by Kelly et al. (1999). Similarly, Othello may derive its drought resistance from Common Red Mexican and Local Pink (a landrace from California) via Sutter Pink. Othello also has in its pedigree a tropical black bean landrace (N 203 synonymous with PI 203958) from coastal Mexico that was extensively used as a source of Fusarium root rot resistance in the USDA-ARS-Prosser, Washington breeding program (Burke et al., 1995; Miklas, 2000).

Identification and judicious use of favorable alleles and QTL present in these drought resistant landrace and cultivars and other landraces such as Apetito (synonymous with G 13637, Padilla-Ramírez et al., 2005) and San Cristobal 83 (Terán and Singh, 2002a), cultivars (e.g., Condor), and breeding lines (e.g., 115M, BAT 477, B 98311, L 88–63, SEA 5) may be pivotal for the future development of highly drought resistant cultivars for dryland and irrigation-assisted sustainable production systems in the western USA. Identification and pyramiding of complementary drought resistant alleles and QTL from other common bean races, gene pools, and related *Phaseolus* species (e.g., *P. acutifolius*) may be worthwhile for long-term sustained genetic progress for drought resistance and improved water use efficiency (WUE).

Cultivation of highly drought resistant dry bean cultivars such as Common Red Mexican, Matterhorn, CO 46348, and Othello should be promoted in areas with endemic drought and recurring water shortage. Under such environments, early maturing drought resistant cultivars such as Othello should help conserve water because they may be grown with less irrigation than the later maturing full-season Common Red Mexican and CO 46348. Higher yielding, early maturing cultivars may also provide flexibility for later planting or earlier harvest, thus avoiding unexpected frost in late spring and early fall. Nonetheless, further studies may need to be conducted to determine irrigation schedules and amount of water to be applied to each drought resistant landrace and cultivar.

In dry bean, seed weight, color, and shape are important components that determine the recovery percentage and commercial value. Drought stress reduced seed weight in both 2003 and 2004. The extent of reduction depended on the level of drought stress and genotypes. For example, under severe drought stress in 2003, UI 259 had the highest reduction (22%) in seed weight, but under moderate drought stress only 9% reduction occurred in 2004. Common Red Mexican and other cultivars that showed limited reduction in seed weight under DS in either year should be preferred over those with marked reduction due to drought stress. Also, it may be worthwhile to determine the genetic basis of seed weight in Common Red Mexican that set it apart from all other cultivars.

ACKNOWLEDGMENTS

Financial support received from the USDA-Western Regional Sustainable Agricultural Research and Education program (Project # WS02-038) from 2002 to 2005 is highly appreciated. C.G. Muñoz was also partially funded through the Graduate Research Assistantship from the Department of Plant, Soil and Entomological Sciences, College of Agriculture and Life Sciences, University of Idaho, Moscow. We are also grateful to R. Hayes, C. Robison, and M. Dennis for their assistance with plot management and soil water potential measurements.

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